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UNDERWATER SHOCK IN THE FAR-FIELD FROM A
DISTRIBUTION OF CHARGES

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Underwater Shock in the Far Field from a Distribution of Charges

Paul van der Schaaf

MRL Technical Report
MRL-TR-91-13

Abstract

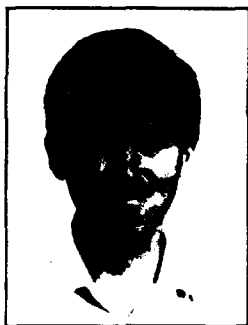
An acoustic model incorporating seabed, sea surface and cavitation effects is used to predict the far field underwater shock from a distribution of explosive charges. A comparison of model predictions with experimental data for phenomena that cannot be considered strictly acoustic shows that such a model provides a useful first approximation, and illustrates some of the errors resulting from the simplifying assumption of an acoustic process.

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Contents

1. INTRODUCTION	7
2. MODEL	8
2.1 <i>Single Charge Shock</i>	8
2.2 <i>Sea Surface Reflection</i>	9
2.3 <i>Seabed Effects</i>	9
2.4 <i>Confluence of Shocks</i>	10
2.5 <i>Calculation of Shock Parameters</i>	11
2.6 <i>Implementation</i>	12
3. RESULTS AND DISCUSSION	12
3.1 <i>Multiple Charges</i>	13
3.2 <i>Line Charge</i>	16
3.3 <i>Two Charges: Effect of Boundaries</i>	17
3.4 <i>Explosive Ordnance Dump</i>	17
4. CONCLUSION	20
5. ACKNOWLEDGEMENTS	21
6. REFERENCES	21

Underwater Shock in the Far Field from a Distribution of Charges

1. Introduction

Predicting the shock parameters from an underwater explosion is normally carried out using the empirically established similitude equations, [1], that assume the explosive to behave as a spherical, centrally initiated charge. This assumption may not be applicable when considering underwater shock from multiple charges, such as might occur when an item of explosive ordnance detonates in an underwater dump causing sympathetic detonation of other items in its vicinity.

Attempting to accurately predict the interaction of shocks from an agglomerate of charges requires the modelling of complex nonlinear effects for which few exact solutions exist [2]. In addition to which there is a paucity of detailed experimental data that could adequately validate a complex model. However a number of simplifying assumptions can be made that would allow a model to be developed that gives a semi-quantitative description of underwater shock in the far field.

Such a model would not only be useful for investigating the effects of sympathetic detonation of multiple charges, but also for predicting the main features of underwater shock from charges that differ substantially from the well researched spherical shape, and in minefield planning where the detonation of two or more mines may significantly increase the distance at which a target is damaged.

This report describes the development of such a model and compares the results obtained with experimental data.

2. Model

When describing underwater shock the parameters of interest are the energy flux density, impulse, peak pressure and some measure of the duration of the shock, e.g. when appropriate, the time constant. Underwater shock from multiple charges clearly does not allow the general application of the similitude equations, (empirically established relationships between the charge mass, distance from the charge and the shock parameters at that distance), to determine the shock parameters. So here it is the pressure-time profile of such a "composite" shock that is modelled from which the parameters are then easily derived.

The features of this model are that it assumes shocks from individual charges to be characterized by the similitude equations; interaction amongst the individual shocks is acoustic, (valid for pressures less than 100 MPa [3]), and therefore the composite shock is simply the linear superposition of the individual shocks; and that it accounts for the boundary effects of the sea surface and the seabed.

2.1 Single Charge Shock

It is assumed that the shock from a charge in free water is equivalent to that from a spherical, centrally initiated charge, in which case the pressure at a distance r from a charge mass m at a time t after the arrival of the shock at distance r is approximated by,

$$P(r, t; m) = \begin{cases} P_{\max}(r; m) \cdot e^{-t/\theta(r; m)}, & t < \theta(r; m) \\ P_{\max}(r; m) \cdot \theta(r; m) / (t \cdot e), & n \cdot \theta(r; m) \geq t \geq \theta(r; m) \\ 0, \dots, & t > n \cdot \theta \end{cases} \quad (2.1)$$

$$e \equiv 2.718 \dots$$

where the function for $t \geq \theta$ accounts for the observed slower than exponential decay of the pressure and n typically ranges between 5 and 10 [4]. The peak pressure $P_{\max}(r; m)$, and the time constant $\theta(r; m)$ for TNT, are given by the similitude equations [1], as

$$\begin{aligned} P_{\max}(r; m) &= 52.4 \cdot m^{0.377} / r^{1.13}, \\ \theta(r; m) &= 0.084 \cdot m^{0.0767} \cdot r^{0.23}. \end{aligned}$$

2.2 Sea Surface Reflection

The reflection of the shock from the sea surface is assumed to be acoustic and is incorporated by the method of images. The boundary condition at this free surface is minimal pressure and is met by placing an image charge so the sea surface forms a plane of symmetry. The reflected shock is then equivalent to a rarefaction, having the same profile as the shock, emitted by the image charge at the same time as the shock is emitted from the charge, Figure 1(a).

Reflection from the sea surface is responsible for the surface cut-off phenomenon, an effect that reduces the duration of a shock and hence its energy flux density and impulse. Its mechanism is as follows, (refer Fig. 1): the shock not only travels directly towards the target, but also along a sea surface reflected path. The surface reflected component of the shock, now a rarefaction, has a longer path and therefore arrives at the target later, (at the "cut-off" time), than the direct shock. Assuming linear superposition would result in a (possibly large magnitude) negative pressure at the target when the surface reflected component arrives. In practice this does not occur; water, especially that with contaminants, has a low cavitation pressure [5] and only supports a comparatively low negative pressure. Here this cavitation-limited minimum pressure is assumed equal to zero. Therefore the resultant shock at the target consists of the shock that propagates along the direct path truncated upon the arrival of the surface reflected component at the cut-off time. After cut-off the pressure remains zero as a result of cavitation.

The effect of surface cut-off increases with diminishing target and/or charge depth. Wherever the shock parameters energy flux density, impulse and the duration are important, neglect of the surface cut-off phenomenon can lead to gross error.

2.3 Seabed Effects

Seabed substructure can have a significant effect on the shock. The substructure is dependent on the geology of the region, the determination of which is itself a discipline. With many unknowns, and not being primarily concerned with shock-substructure interaction, seabed effects are simply approximated by assuming that the presence of the seabed affects the explosive's yield and hence the explosive can be considered as equivalent to a freewater charge of the appropriate mass. The seabed reflection factor (SRF), is then defined as the ratio of this equivalent freewater explosive mass to the mass of explosive on the seabed. The SRF is dependent on the "hardness" of the seabed. Later the SRF is assumed equal to 1.3 which is within the range of the SRF given by [1]. Note that this factor is for an explosive charge on the seabed and not otherwise as "reflection" may connote.

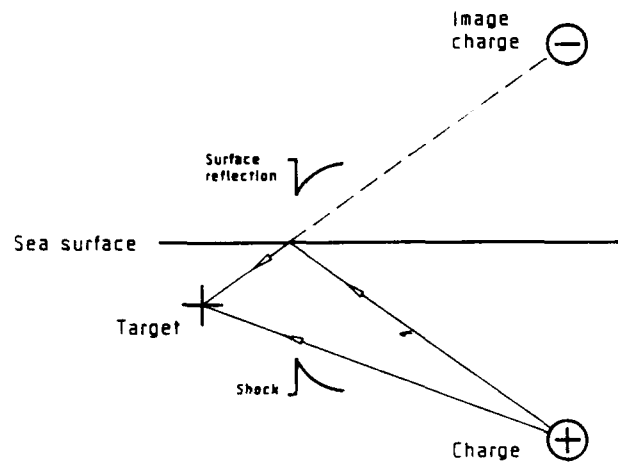


Figure 1(a): Sea surface reflection by method of images.

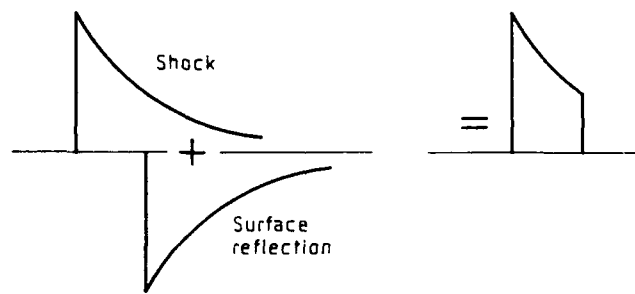


Figure 1(b): Superposition of shock and sea surface reflected shock including the effects of cavitation.

2.4 Confluence of Shocks

The confluence of shocks is assumed to be a linear superposition with the added effects of cavitation. In the case of multiple charges it is important to complete the superposition of all shocks and their surface reflections before cavitation effects are accounted for, and not as may be suggested by a single charge, that the shock and its surface reflection are superposed and corrected for cavitation before interaction with other shocks is considered.

Clearly this process of confluence can cause the composite shock to have enhanced shock parameters, but now the possibility exists for surface cut-off to markedly reduce these parameters in a manner unique to the multiple charge scenario. For a single charge surface cut-off occurs as a result of the shock

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CORRIGENDA

The following text was omitted from the end of the final paragraph on page 10

"interacting with its surface reflection. This self-interaction implies that the surface reflection lags the shock and therefore the surface cut-off phenomenon removes energy flux density and impulse firstly from the tail moving towards the head of the shock (removing additional energy flux density)".

This sentence continues at the top of page 11.

as the effect increases. With multiple shocks, unlike the case for the single charge, the shock is not constrained to interact with only its surface reflection. The possibility of interacting with the surface reflection of another shock means surface cut-off effects could occur at the head of a shock for probable geometries whereas for the single charge this would only be approached in extreme cases. Hence surface cut-off effects for multiple charges can be greater than estimates based on a single equivalent mass charge.

2.5 Calculation of Shock Parameters

The above scheme determines the pressure-time profile of the composite shock from multiple charges. In the far field this shock is assumed to be plane in which case the energy flux density, EFD , and impulse, I , are given by [1] as,

$$EFD(r;m) = (1/(\rho c)) \cdot \int_0^{\pi\theta} P(r,t;m)^2 dt \quad (2.5a)$$

$$I(r;m) = \int_0^{\pi\theta} P(r,t;m) dt \quad (2.5b)$$

Here $n = 7$ is chosen as it gives good agreement with the similitude equations, the choice being somewhat arbitrary [4]. Setting the acoustic velocity in sea water to $c = 1530 \text{ ms}^{-1}$ and the density to $\rho = 1025 \text{ kg.m}^{-3}$, then equations 2.5 with $P(r, t; m)$ given by equation 2.1 give the energy flux density and impulse to within $\pm 5\%$ and $\pm 3\%$ of that determined by the respective similitude equations for peak pressures between 3.5 and 50 MPa.

Some investigations of shock phenomena assume an exponential pressure decay (unlike equation 2.1 which is only partly so). This has some desirable analytical features and usually requires less computational effort to implement. However given the aforementioned range of peak pressures, the energy in such a form is 93% to 87%, and the impulse is 76% to 72% of the parameter values determined by the similitude equations. The exponential form is of a comparable accuracy only for $t < \theta$, and therefore in this instance is rejected in favour of the pressure-time function given by equation 2.1.

2.6 Implementation

Computer code was written to implement the model thus allowing convenient investigation of particular charge distributions. The code operates by reading a data file in which the position of each charge and its equivalent charge mass in kilograms of TNT, the target position and the depth of water are specified. The initiation time, also contained in the data file, of each charge can be preset or a particular charge can be nominated to sympathetically detonate the remainder of the charges, as for example may occur in explosive ordnance dumps. In such circumstances the position and sensitivity of the charges may be difficult to ascertain. In allowing for the worst case no attempt was made to model the sympathetic detonation mechanism except in as much as the initiation time of a piece of explosive ordnance is determined by the arrival time of the shock from the nominated "initiator". The velocity of the shock from the "initiator" can be specified independently of the underwater shock velocity, reflecting the fact that a shock capable of causing sympathetic detonation may have a velocity higher than the far field underwater shock velocity. Having read or created a data file the code increases the charge mass by the seabed reflection factor, here assumed equal to 1.3. The shock parameters characterizing the shock and its surface reflection at the target site for each charge are determined. Finally addition of the individual shocks and their sea surface reflections including cavitation effects results in the pressure-time profile of the composite shock. The energy flux density and impulse are then found via equations 2.5.

3. Results and Discussion

An acoustic model with its relative simplicity provides an expedient method to investigate shock from multiple charges. In instances for which the shock interaction cannot be considered acoustic, it is necessary to examine the validity of the acoustic approximation. The utility of this model must be considered in terms not only of possible error inherent in the acoustic approximation but also the quality of the data used to specify the problem and the intended use of the model's output.

The manner in which shocks interact is determined by their pressures and hence is also dependent in some way on the charge separation. Here the separation is used in an approximate manner to delineate shock interaction into three regimes as suggested by Shanes, [6]: when charges are in close proximity they tend to behave as a single charge of the same total mass; at a greater separation where pressures are still sufficiently large, shock behaviour is nonlinear, e.g. resulting in the formation of Mach stems etc; further increasing the separation results in decreasing interaction pressures which when low enough imply that shock interaction is predominantly acoustic.

A comparison with experiments [7, 8] illustrates some of the deficiencies of modelling in the nonacoustic regimes. The first experiment considered is the simplest possible multiple charge distribution, the detonation of two charges, the second being the detonation of a line charge. The two remaining

simulations are hypothetical; firstly two charges detonated simultaneously, illustrating surface cut-off effects and the directional properties of the shock when compared with a single equivalent mass charge; the last example compares the shock from a single charge with the shock from an explosive ordnance dump, simulated by a distribution of charges of the same total mass.

3.1 Multiple Charges

Booker and Harrington [7], conducted experiments to measure the shock parameters for particular directions and distances from two asynchronously detonated 0.567 kg TNT charges separated by 0.152 m of water.

In the model the experimental geometry is retained, Figure 2(a), but the delay time determined by the length of detonation cord and its velocity of detonation is not. The experiment showed that the difference in the shock arrival times to be less than the difference in the detonation times of the charges. This is not unexpected as the higher pressures in the near field also imply a greater shock velocity. For better agreement of model predictions with experimental results in the far field the acoustic assumption requires that the difference in the arrival times of the shocks be used as the detonation delay in the model.

Results of both the model and the experiment were recorded as a percentage of the respective shock parameters for the single equivalent mass charge. The results are shown in Figures 2(b)-(d). Each graph is for a particular shock parameter at a fixed distance and detonation delay against the angle α .

Model predictions of peak pressure are reasonable. Predictions of energy flux density show a greater error though a trend similar to the experimental data exists. Impulse predictions are in poor agreement, both in magnitude and directional properties.

Impulse scales linearly in pressure and time (equation 2.5b). This, considered with the reasonable model estimates of peak pressure, suggests that the error in estimates of impulse principally result from factors affecting the duration of the shock. While energy flux density (equation 2.5a) is also affected by the duration of the shock, this parameter has a quadratic dependence, and therefore greater sensitivity on pressure. Hence the greater error of model estimates of energy flux density and the similar trend, via the quadratic dependence on pressure, between energy flux density and peak pressure.

As the model determines the resultant pressure by linear superposition, which strictly is only true for an acoustic interaction, it is suspected that in this instance the delay between the detonation of the two charges allows sufficient time for the shock pressure of the first detonated charge to decay to a level where the interaction with the shock from the second charge is weakly acoustic. It may also be possible that nonacoustic behaviour in the near field is to some extent masked by the effects of distance, the expected acoustic behaviour becoming prominent as the shock pressure decreases, and hence the reasonable agreement of model estimates of peak pressure with the experimental data.

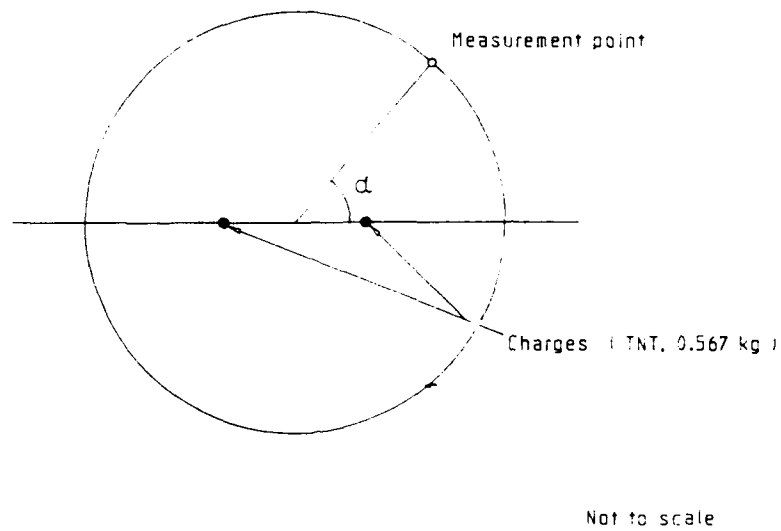


Figure 2(a): Experiment's geometry.

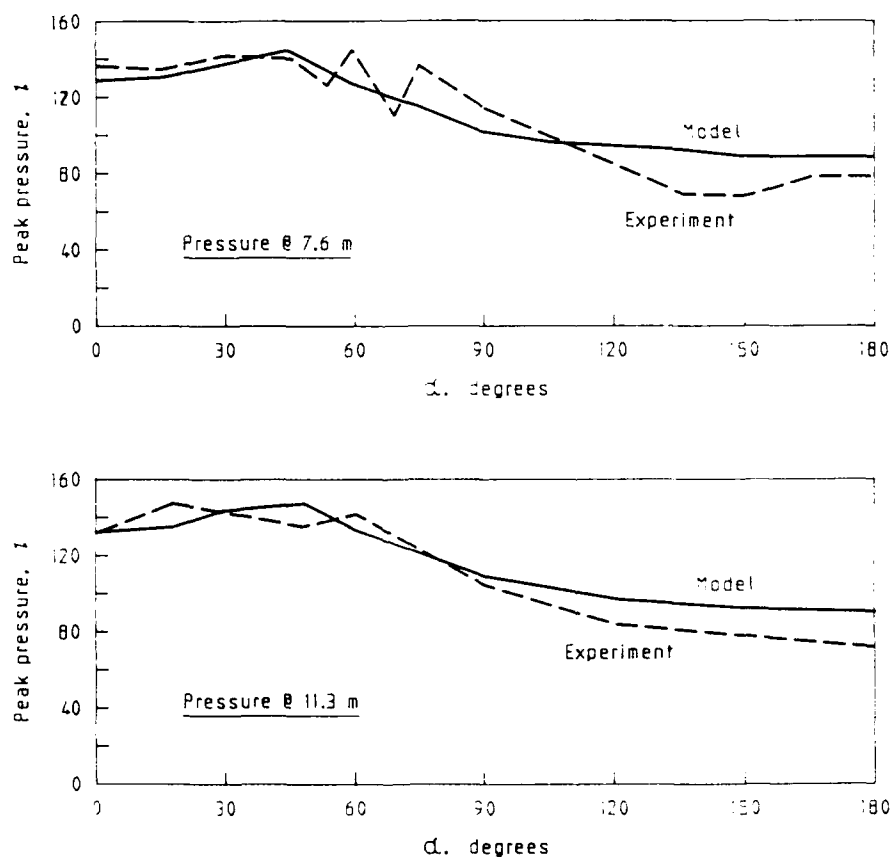


Figure 2(b): Pressure relative to a single equivalent mass charge.

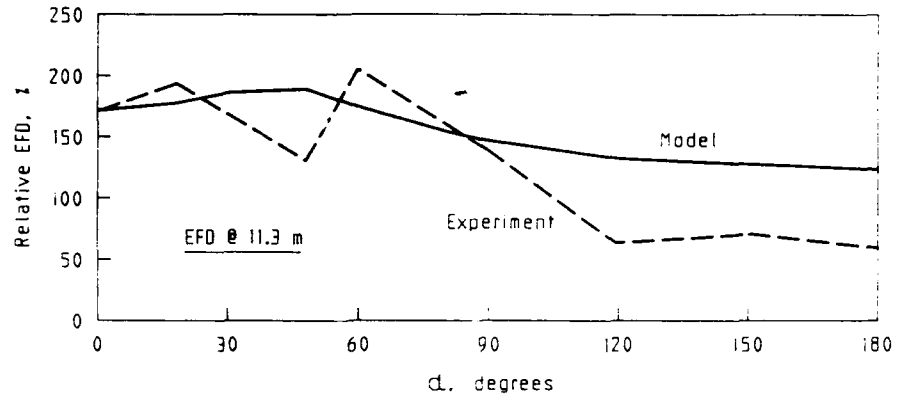
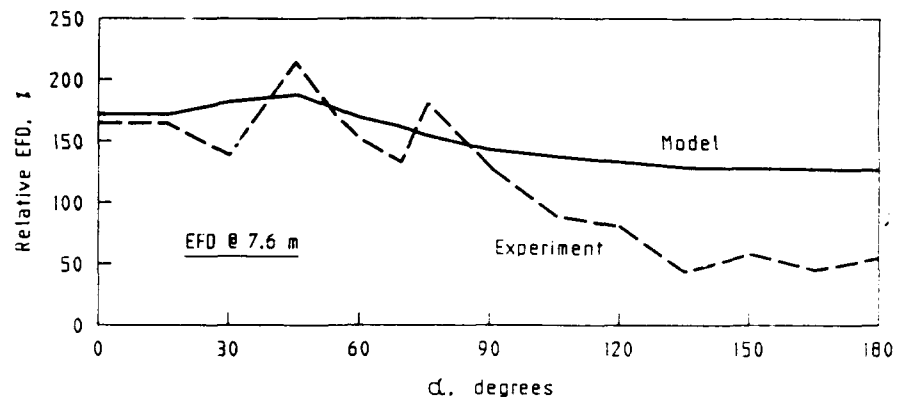


Figure 2(c): Energy flux density relative to a single equivalent mass charge.

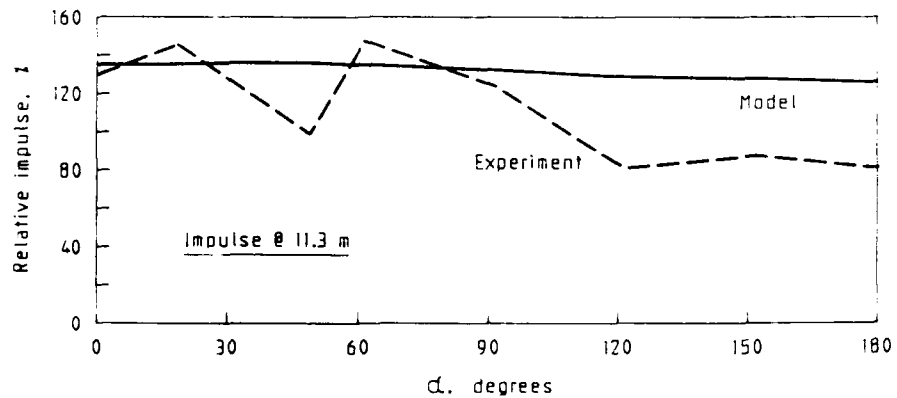
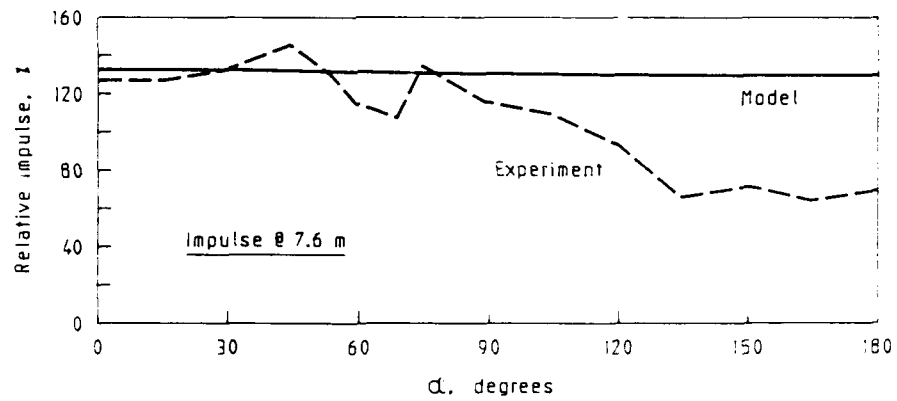


Figure 2(d): Impulse relative to a single equivalent mass charge.

3.2 Line Charge

Following Charlesworth and Bryant [8], a line charge is modelled as a set of collinear "elemental" charges. A charge is detonated according to the arrival time at the charge of what is considered as the detonation front originating from the initiator charge, otherwise the shock is considered acoustic. A comparison was made with experimental data [9]. The model replicated the form of the shock and its duration well, Figure 3, excepting the relatively slow pressure increase at the shock front. The estimates of pressure were poor and therefore also the estimates of energy flux density and impulse.

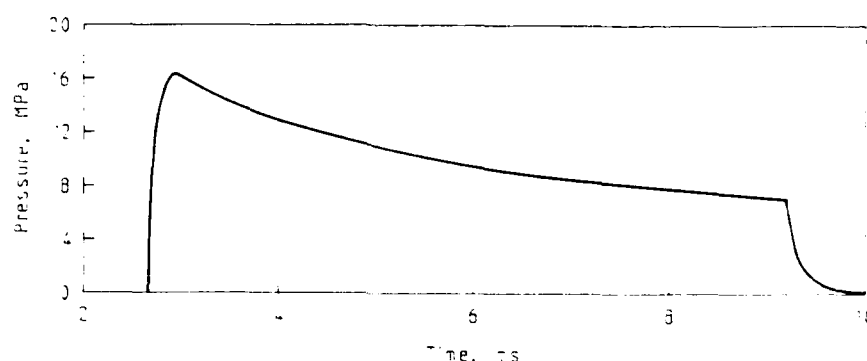


Figure 3: Underwater shock on axis of modelled line charge.

Charlesworth and Bryant's seemingly reasonable agreement with the experimental data results from their (arbitrary) choice of the peak pressure and time constant characterizing the shock from the elemental charges. The model developed here does not have such freedom, the elemental shocks being characterized by the similitude equations. However the shock parameters do scale with the number of elements used to model the line charge. For the purpose of argument consider the peak pressure. The similitude equation gives the peak pressure's dependence on the charge mass as $P_{\max} \propto M^{1/3}$. Now assume the charge to be composed of δ pieces of mass M/δ , as acoustic interaction is linear then it is possible that the pressure is the sum of the contributions from the elements, therefore $P_{\max} \propto \delta \cdot (M/\delta)^{1/3} = \delta^{2/3} M^{1/3}$. So when considered as the latter the pressure is enhanced by a factor of $\delta^{2/3}$ when compared with the single equivalent mass charge. Similar arguments hold for the parameters impulse and energy flux density. In addition this scaling is affected by the geometry of the charge and hence a simple rescaling factor based solely on the number of elements chosen to model the charge does not exist. However, the model does succeed in predicting the general qualitative behaviour of the line charge.

3.3 Two Charges: Effect of Boundaries

As yet the effects of boundaries have not been investigated. In this example the effects of the sea surface and the seabed are demonstrated. The pressures, compared with the preceding examples, are comparatively low and as such the model is expected to give a reasonable description of the resulting shock.

Two explosive charges each of 700 kg, separated by 20 m, rest on a seabed with a seabed reflection factor of 1.3 in 20 m of water.

Figure 4 graphs the energy flux density, peak pressure and impulse respectively on a circle of 50 m radius, at a depth of 2 m, centred on the midpoint of the line joining the two charges, with the angle α measured between the line joining the two charges and the radius of the circle. For comparison the appropriate shock parameter from a 1400 kg charge is also graphed.

Variation of the shock parameters with α results from the three effects of: changing distance from the charges to the point in question, surface cut-off, and the amount by which the shocks from each charge coincide.

Consider Figure 4. The decrease in the shock parameters from 0° to approximately 80° is primarily the effect of geometry on distance. At 85° the shock parameters have a minimum due to the surface reflection of one shock interacting with the other shock in the manner described in section 2.4. Here surface cut-off reduced the energy flux density of the two charges by 68% while for the single equivalent mass charge the reduction was only 32%, impulse was reduced by 68% for the two charges compared with 62% for the single equivalent mass charge. For this geometry the peak pressure of a single shock is unaffected by surface cut-off. This is not the case for multiple shocks, here surface cut-off reduced the peak pressure by 26%. At 90° not only is there an enhancement due to superposition but the composite shock is delivered over a shorter period and is therefore less affected by surface cut-off; the peak pressure, impulse and energy flux density of the composite shock from the two charges are 51%, 42% and 105% greater than the respective shock parameters of the single equivalent mass charge.

It is clear in this case that the manner in which multiple shocks interact does not allow a single equivalent mass charge to be used as a simplification without introducing substantial error.

3.4 Explosive Ordnance Dump

It was not intended to model an explosive ordnance dump in great detail. The primary objective was to determine whether the inclusion of effects to model multiple charge shock, though only approximate, would introduce any markedly systematic reduction in shock parameters when compared with the results obtained by treating the dump as a single lumped charge and using established methodology.

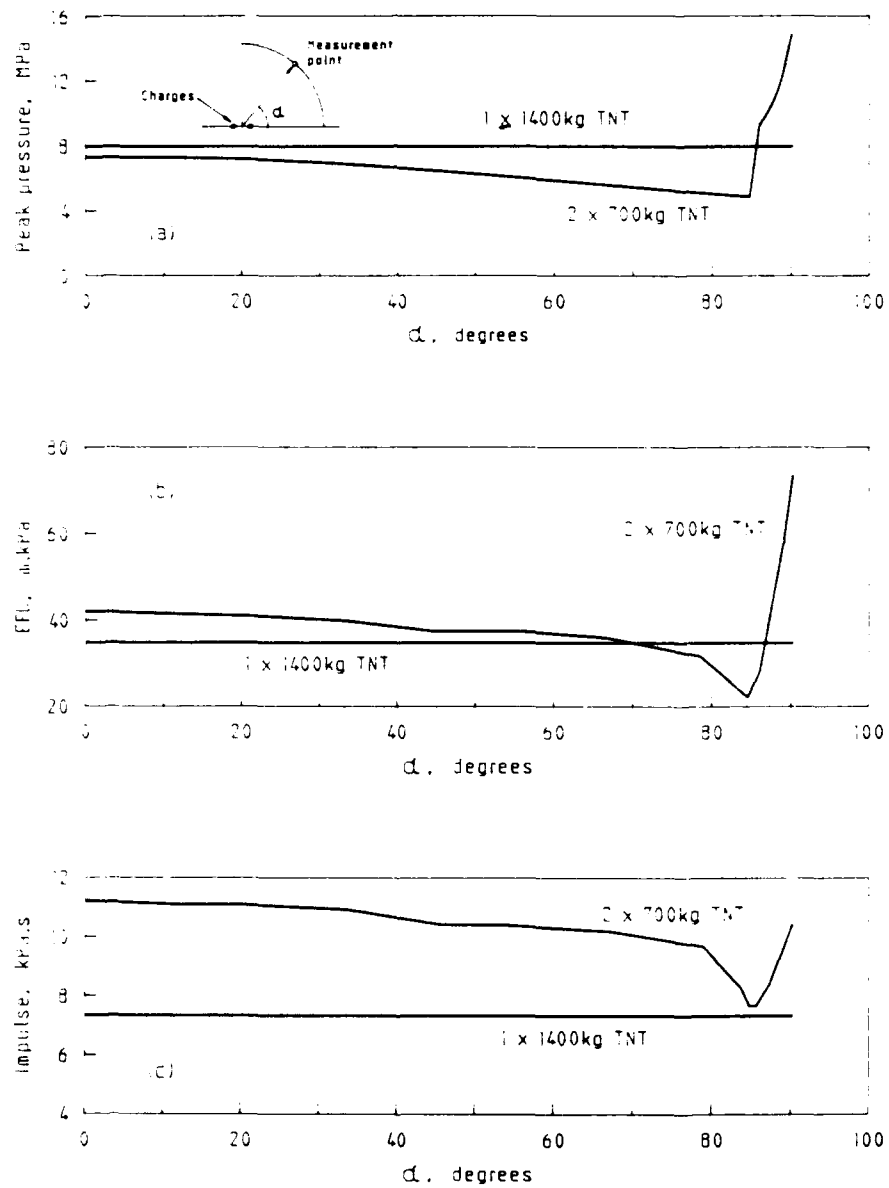


Figure 4: Variation of shock parameters resulting from geometry and sea surface reflection effects dependence on α .

For example, consider the shock from a dump consisting of 60 ground charges each of 500 kg TNT arbitrarily distributed within a circular region of radius 28 m in 30 m of water compared with that from a charge of the equivalent total mass, 30 000 kg TNT, in 30 m of water. The target is at a standoff distance of 200 m at a depth of 10 m.

The shock from the single equivalent mass charge, Figure 5(a), has the expected pressure-time profile with truncation occurring at a time determined by the surface cut-off phenomena and is therefore sensitive to the comparative proximity of the charge and/or target to the sea surface. However the shock from the explosive ordnance dump, Figure 5(b), has a complex pressure-time profile dependent on the temporal sequence of the shocks and their surface reflections from the individual charges and is therefore dependent on the geometry of the charges and target position and on the initiation times of the charges. Here as the effect of surface cut-off increases the composite shock becomes similar to a train of pressure spikes.

Table 1 compares the shock parameters for the dump with initiation by a nominated charge, and the single equivalent mass charge. Note that here it is shown that the shock parameters are sensitive to the position of the initiating charge, but for the present purposes the location of the initiator is not important. Comparison of the two sets of parameters shows that the peak pressure for the explosive ordnance dump is both greater and less than that for the single charge. The energy flux density and the impulse tend to be greater, more so the impulse, than that for the single charge.

Table 1: Shock parameters of the "explosive ordnance dump" upon initiation by the nominated charges and the single equivalent mass charge.

Initiator	P_{\max} (MPa)	Energy Flux Density (m.kPa)	Impulse (kPa.s)
Simultaneous	4.42	42.9	30.0
Charge 31	5.93	43.9	33.6
Charge 39	5.03	52.7	30.0
Charge 42	8.20	53.0	29.7
Charge 58	5.30	52.1	31.5
Charge 1	5.50	57.8	34.4
Single Equivalent Mass Charge			
	7.01	42.4	11.6

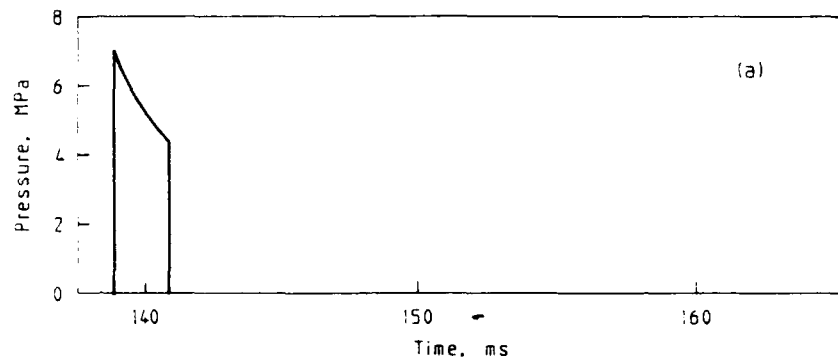


Figure 5(a): Shock from the single equivalent mass charge.

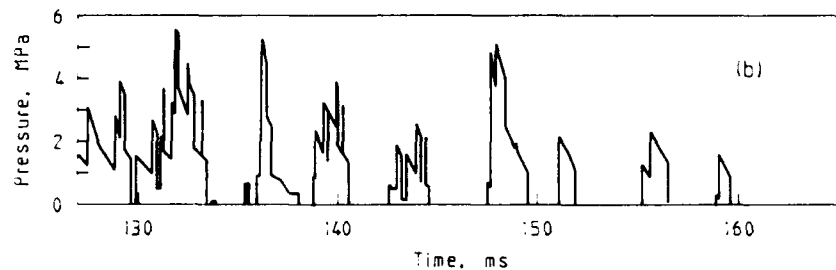


Figure 5(b): Shock from the "explosive ordnance dump".

The composite shock for the explosive ordnance dump and the shock for the single charge can be quite dissimilar. There is nothing to indicate, given the assumptions of this model, that an explosive ordnance dump should have shock parameters that are systematically and markedly reduced when compared with the single equivalent mass charge. In fact in this instance the model predicts the converse for energy flux density and impulse. The scaling phenomenon noted in section 3.2 suggests that there exists a charge density for the explosive ordnance dump above which this model will overestimate the shock parameters.

4. Conclusion

From the experiments considered it has been shown that this model gives reasonable approximations of particular aspects of underwater shock parameters. For example, the peak pressure and its directivity for the multiple charges, section 3.1, and the general qualitative behaviour of the shock from a line charge, section 3.2, are reproduced. As expected the model does not

provide an all-encompassing description of shock in all circumstances.

The surface cut-off effect, caused by shock reflection off the sea surface, can greatly effect the shock. It was shown that for two explosive charges (and hence similarly for any sparse distribution) that the nature of the shock interaction precludes the use of a single equivalent mass charge as a valid simplification. For a dense distribution such as the explosive ordnance dump, section 3.4, surface cut-off changed the shock's pressure-time profile greatly but did not produce any markedly systematic reduction in shock parameters when compared with the single equivalent mass charge. The increase in energy flux density and impulse found for the particular example presented could be an artifact of the model.

The limited comparison made with experimental data for nonacoustic regimes shows that it is important to identify parameters that indicate the nature and magnitude of errors resulting from the acoustic approximation. To this end it is suggested that an analytic investigation of the ramifications of near field nonlinear behaviour on far field underwater shock be made.

5. Acknowledgements

I would like to express my appreciation for the advice and guidance John Bishop has given throughout the preparation of this report.

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ABSTRACT

An acoustic model incorporating seabed, sea surface and cavitation effects is used to predict the far field underwater shock from a distribution of explosive charges. A comparison of model predictions with experimental data for phenomena that cannot be considered strictly acoustic show that such a model provides a useful first approximation, and illustrates some of the errors resulting from the simplifying assumption of an acoustic process.

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Distribution of Charges

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